

Deep-Mine Void Detection through Electrical Imaging

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ABSTRACT

In the late 1800s, shallow subsurface mining of a local coal bed beneath a 25-foot thick sandstone resulted in mine voids in the Akron, Ohio area. Recently, localized subsidence in the subdivision overlying the deep mine has prompted officials to determine if the homes are at risk. Electrical imaging was selected for determining the extent of the subsurface voids.

Shallow-focused electrical imaging profiles were collected near approximately 70 homes. Elevated measured apparent resistivity values indicate areas of subsurface voids or zones of fracturing related to adjacent voids.

An analysis of five parameters within a decision matrix indicates that roughly 25 homes have subsurface anomalies that warrant further investigation. Forty-four homes were not interpreted to have subsurface anomalies that warrant further investigation. Of the 25 homes considered at risk, 9 are considered low risk and 6 are considered high risk.

INTRODUCTION

Electrical imaging can be an effective method for locating subsurface voids, specifically those from mine voids (Hutchinson and Barta, 2002; Orr, et al., 2002). A subdivision within the City of Barberton was developed on a shallow, unmapped abandoned underground coal mine. Due to the age of the coal mine, the shallow overburden above the mine, fluctuating groundwater conditions, and recent land development in the area, conditions are ideal for subsidence. The subsurface movement can cause extensive property damage and poses as a threat to the public health and safety.

The Ohio Department of Department of Natural Resources Division of Mineral Resources Management initiated the Barberton Mine Stabilization Project to define the limits of the unmapped abandoned underground coal mine using drilling and electrical imaging methods. Initial drilling efforts revealed a number of voids, collapsed areas and inplace coal (Figure 1).

The initial drilling program indicated that the occurrence of coal was local and not easily determined; consequently, voids would be difficult to locate and remediate. Twenty-five borings of 47 advanced, encountered mined-out areas (void, collapsed void, fractured overburden); 12 borings recovered coal, and 10 encountered non-coal deposits (Collins, 2001). An earlier

investigation concluded that 1 church, 1 school, and potentially 56 homes lie above the mined out area.

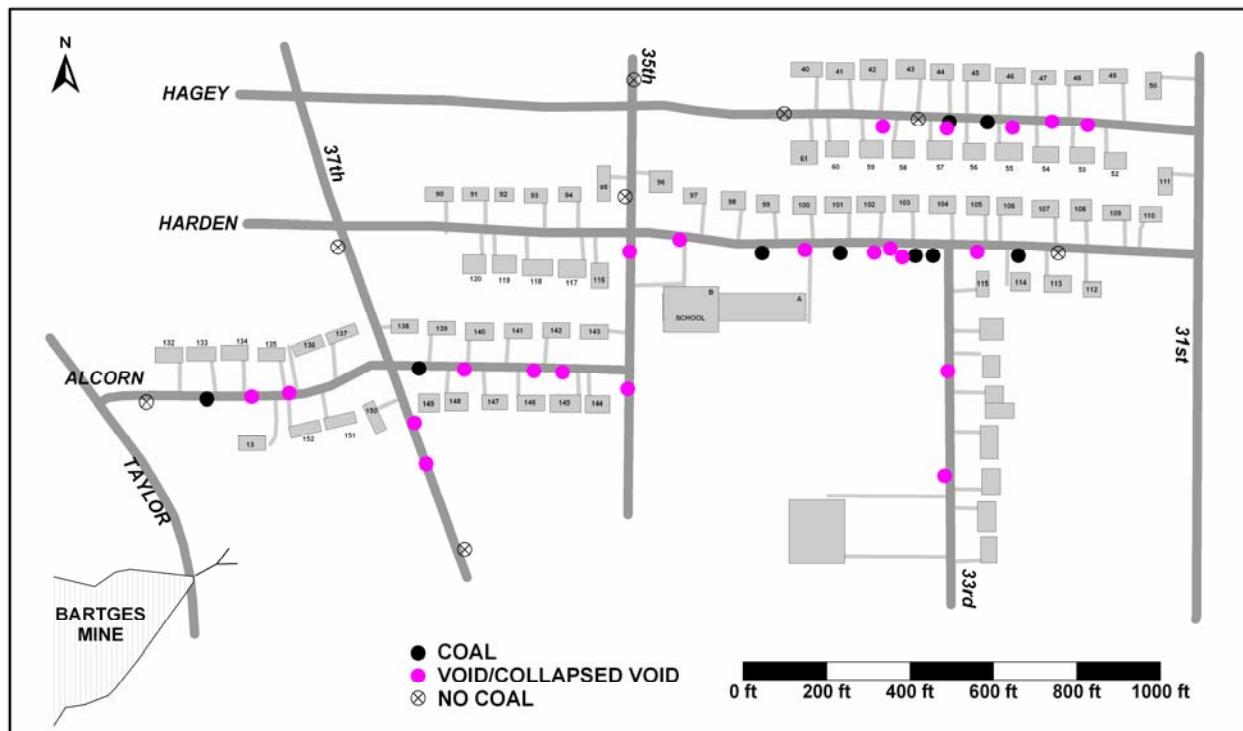


Figure 1. Location of borings in the Barbarton subdivision showing the occurrence of voids, coal, and non-coal deposits.

GEOLOGY

The site is located in Summit County, which is within the glaciated portion of the Appalachian Plateau region of Ohio (Heath, 1988). The soil in the study area consists of Wisconsin(?) -aged till described as brown silt and sand with lesser proportions of clay that ranged in thickness from 3.0 feet to 15.0 feet, however, most soil extended somewhere in the range of 10.0 to 12.0 feet in depth (Collins, 2001).

Bedrock is relatively flat-lying and described as a weathered, brown sandstone unit, with visible red (rust) staining. The sandstone unit, the Massillon Sandstone, contains an intercalated dark gray shale and is the roof material for the coal mine. Below the coal lies an approximately 2-foot thick under clay. The sandstone and coal are part of the Mississippian-aged Pottsville Formation. The deep-mined coal is designated as the Sharon (#1) coal.

The area of distribution of the Sharon (#1) coal seam in Summit County is localized due to deposition on uneven terrain and local erosion and deposition. The 10- to 25-foot thick Massillon Sandstone overlies the Sharon coal and locally replaces the coal entirely; resulting in a feature referred to as a “horseback.”

Recorded coal-mining activity occurred across the valley (i.e., west of the study area) at the Bartges mine (Map St-14; Delong, 1981). The A.F. Bartges Company operated the mine in the late 1870's and abandoned operations in 1876. The Sharon (#1) coal was removed using the drift entry method of coal extraction. The mine map shows that the face cleat is oriented N28°E. Coal was removed either commercially or privately from this area; however, no deep-mine maps exist for the study area.

ELECTRICAL IMAGING

Theory

Electrical resistance is based upon Ohm's Law:

$$R = \frac{V}{I} \quad (1)$$

Where, resistance, **R**, is equal to the difference between the current flow, **I**, and voltage differential, **V**. However, resistivity depends upon the bulk property and geometry of the material. Consequently, resistivity is measured in Ohm-meters.

Currents are carried through earth materials by motion of the ions in connate water. Ions in connate water come from the dissociation of salts and provide for the flow of electric current. Further, resistivity decreases in water-bearing rocks and earth materials with increasing:

1. Fractional volume of the rock occupied by water;
2. Salinity content of the water;
3. Permeability of the pore spaces; and,
4. Temperature.

Materials that lack pore space (i.e., limestone, igneous rocks) or lack water in the pore space will show high resistivity (Mooney, 1958). Most earthen materials, however, show medium to low resistivity.

In homogeneous ground, the apparent resistivity is the true ground resistivity; however, in heterogeneous ground, the apparent resistivity represents a weighted average of all formations through which the current passes. Many electrode placements have been proposed (for examples, see Reynold, 1998); however, the Schlumberger configuration has proven to be an effective configuration for imaging voids in bedrock settings. The following Schlumberger configuration was used in the collection of data:

$$R_i = \frac{\pi a^2}{b} \left[1 - \frac{b^2}{4a^2} \right] R; a \geq 5b \quad (2)$$

Where, R_i , resistivity, is related to the number of poles, n , the separation of the current source b , and pole spacing, a , is from Ohm's Law.

Maximum imaging depth (i.e., resolution) is based upon electrode spacing for this survey and was derived from:

$$D = \frac{BA}{2} + \frac{AM}{2} \quad (3)$$

Where, the depth, D , is a function of the pole spacing for the electrodes, A , B , and M . The pole spacing for the collection of data in the range of interest for the site is 4 meters.

Methodology

The resistivity survey was performed using the ARS200 multi-electrode cable system (GF Instruments, s.r.o., Brno, Czechoslovakia). The survey was conducted using stainless-steel electrodes and stainless-steel cylinder-bearing cables.

Seven Schlumberger array resistivity survey lines were collected parallel to Alcorn, Harden, and Hagey Streets and as close to the building structures as physically possible. The 2 profile lines on Alcorn are approximately 1,770 feet long; the 2 profile lines on Harden are approximately 1,560 feet long; the 2 profile lines on Hagey are approximately 830 feet long; and one profile line immediately south of the school building is approximately 300 feet long. A total of over 10,000 linear feet of resistivity data were collected.

A forward modeling subroutine was used to calculate the apparent resistivity values using the RES2DINV program (Loke, 1998). This program is based upon the smoothness-constrained least-squares method (deGroot-Hedlin and Constable, 1990; Loke and Barker, 1996). The smoothness-constrained least-squares method is based upon the following equation:

$$J^T g = (J^T J + \mu F) d \quad (4)$$

Where, F is a function of the horizontal and vertical flatness filter, J is the matrix of partial derivatives, μ is the damping factor, d is the model perturbation vector and g is the discrepancy vector.

The RES2DINV program divides the subsurface 2D space into a number of rectangular blocks. Resistivities of each block are then calculated to produce an apparent resistivity pseudosection. The pseudosection is compared to the actual measurements for consistency. A measure of the difference is given by the root-mean-squared error.

ANALYSIS

Elevated measured apparent resistivity values are interpreted to be subsurface voids or zones of fracturing related to adjacent voids. In a relatively flatlying homogeneous clastic stratigraphic setting, the resistivity profiles should show horizontal bedding; however, non-horizontal phenomenon are interpreted to be subsurface voids. Resistivities of less than 90 were considered background and resistivities between 90 and 200 were considered to be anomalous (Figure 2).

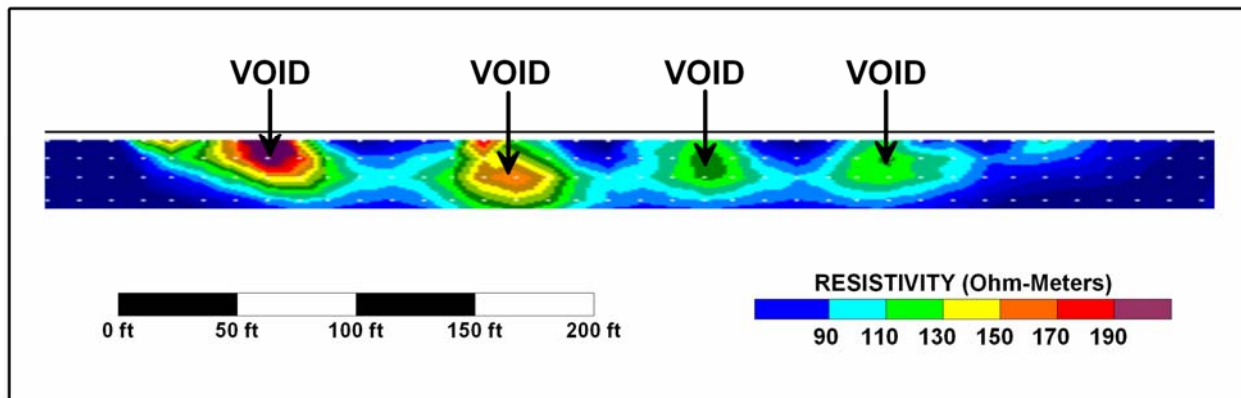


Figure 2. Elevated apparent resistivity values indicative of coal mine voids (no vertical exaggeration).

The area investigated shows obvious signs of subsidence and many residents complained of the appearance of holes in their yards. The resistivity profiles show that several voids exist in the shallow subsurface at the site (Figure 3).

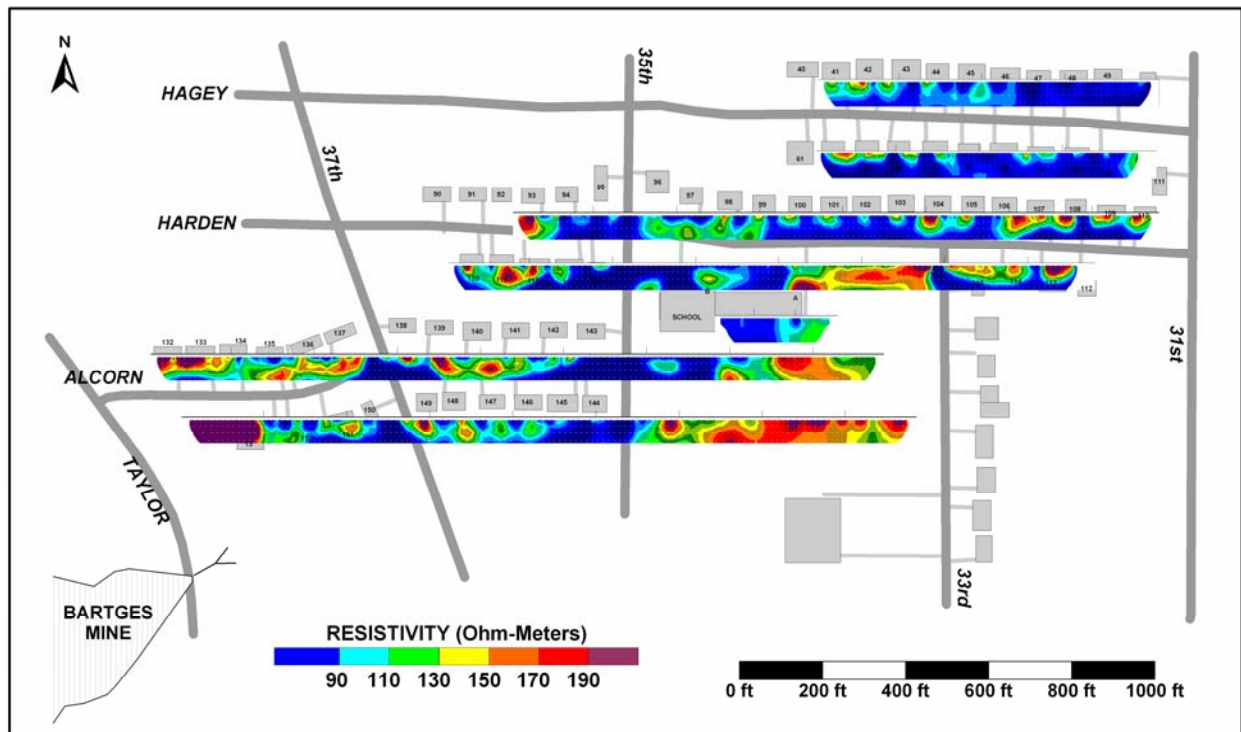


Figure 3. Seven electrical imaging lines located along the profile spatial position; showing undisturbed rock in dark blue and voids in red (no vertical exaggeration).

A decision matrix was used to assign a hierarchy to the subsurface phenomenon observed in the subsurface in front of the homes. This hierarchy is based upon a subjective number assignment of from 1 to 5 where an assignment of 5 indicates the maximum characteristic possible for the matrix descriptor (Table 1).

HOUSE NO.	VOID PRESENT	INTENSITY	DEPTH	PROXIMITY	SIZE	TOTAL
13	0					0
41		3	1	2	2	8
42		4	1	2	3	10
43	0					0
44		3	1	2	2	8
45		3	5	3	5	16
46		1	5	3	3	12
47	0					0
48	0					0
49	0					0
50	0					0
52	0					0
53	0					0
54		3	1	3	2	9
55	0					0
56	0					0
57		3	2	5	3	13
58		3	2	4	3	12
59		4	2	4	4	14
60		4	3	4	4	15
93	0					0
94	0					0
95	0					0
96		3	5	3	5	16
97		3	5	4	5	17
98		4	5	4	5	18
99		3	5	4	5	17
100		3	2	5	3	13
101		3	2	4	3	12
102	0					0
103		2	2	3	2	9
104		5	4	4	5	18
105		4	3	4	3	14
106		5	5	4	5	19
107		4	3	4	3	14
108		5	2	5	3	15
109		4	2	5	3	14
110		4	2	5	3	14
113		4	3	1	4	12
114		4	4	3	4	15
115		4	4	4	5	17
SCHOOL A		5	5	3	5	18
SCHOOL B		3	5	4	5	17
116	0					0
117		4	3	5	4	16
118		5	4	5	4	18
119		5	5	5	5	20
120		5	3	2	3	13
132	0					0
133	0					0
134	0					0
135		5	5	4	5	19
136		5	5	3	5	18
137		5	5	3	5	18
138		5	1	3	3	12
139		5	5	3	5	18
140		5	5	5	5	20
141		3	4	4	5	16
142		2	2	4	2	10
143	0					0
144	0					0
145	0					0
146		3	5	5	5	18
147		3	5	5	5	18
148		4	5	5	5	19
149		5	4	5	5	19
150		4	4	4	5	17
151		3	3	3	4	13
152		3	5	4	5	17

Table 1. Matrix analysis of the Barberton deep-mine apparent resistivity anomalies.

Five descriptors utilized in the ranking of the subsurface phenomenon:

- Void Present - No void is present if an apparent resistivity below 90 Ohm-meters exists in front of a house;
- Intensity - When a void is present a number from 1 to 5 is assigned based upon the strength of the apparent resistivity reading, where 5 indicates an apparent resistivity of 200 Ohm-meters;
- Depth - The depth was assigned a value of between 1 to 5 based upon how close the phenomenon was to the actual inferred depth of the deep-mine void (25 to 30 feet below grade); shallow phenomenon were interpreted to be fractures that had propagated vertically upwards from an adjacent mine void;
- Proximity - The proximity of the line to the home was considered important in providing a hierarchy to those homes with the potential for subsidence; and,
- Size - Size was considered important since large anomalies (assigned a value of 5) may represent a greater hazard than small anomalies.

Electrical profiles imaged the subsurface in the front of 69 homes; of which 25 homes were considered to have a subsurface anomaly that may warrant further investigation (matrix value of greater than 16). Forty-four homes were not interpreted to have a subsurface anomaly that warrants further investigation. Of the 25 homes considered at risk, 9 are considered low risk (matrix value of between 16 and 18) than and 6 are considered high risk (matrix value of greater than 19; Table 1; Figure 4).

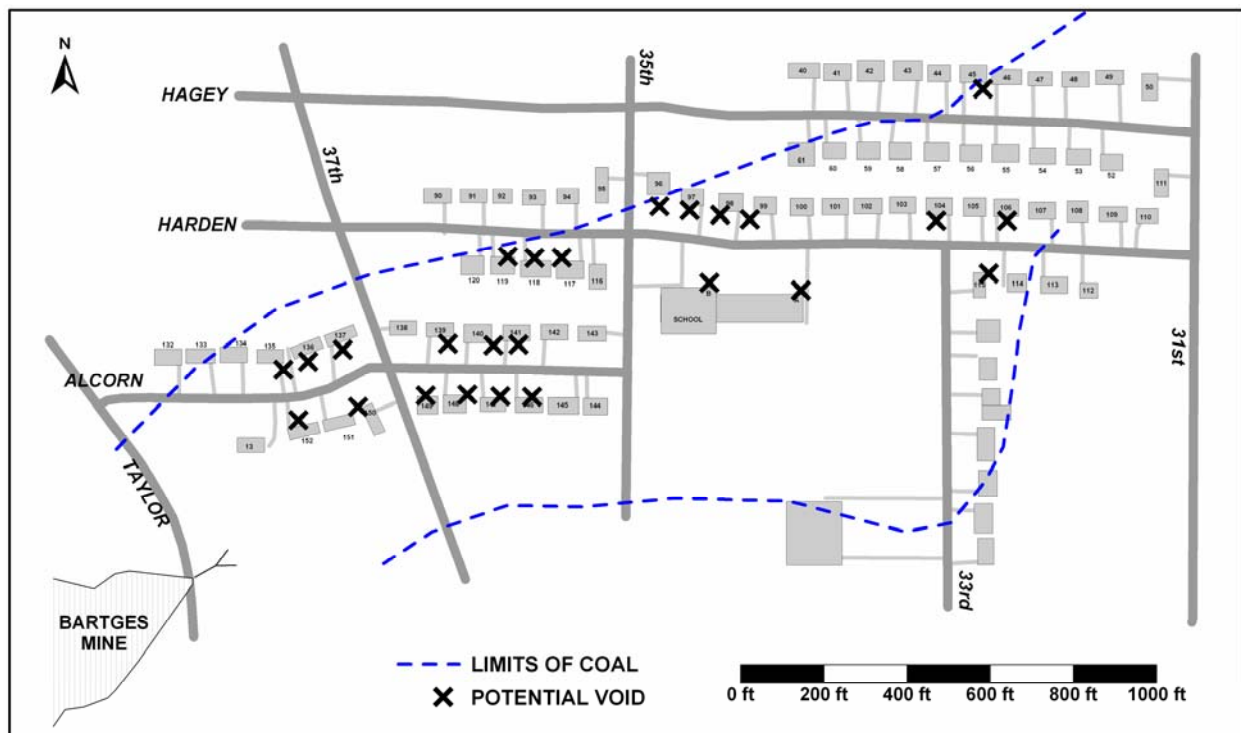
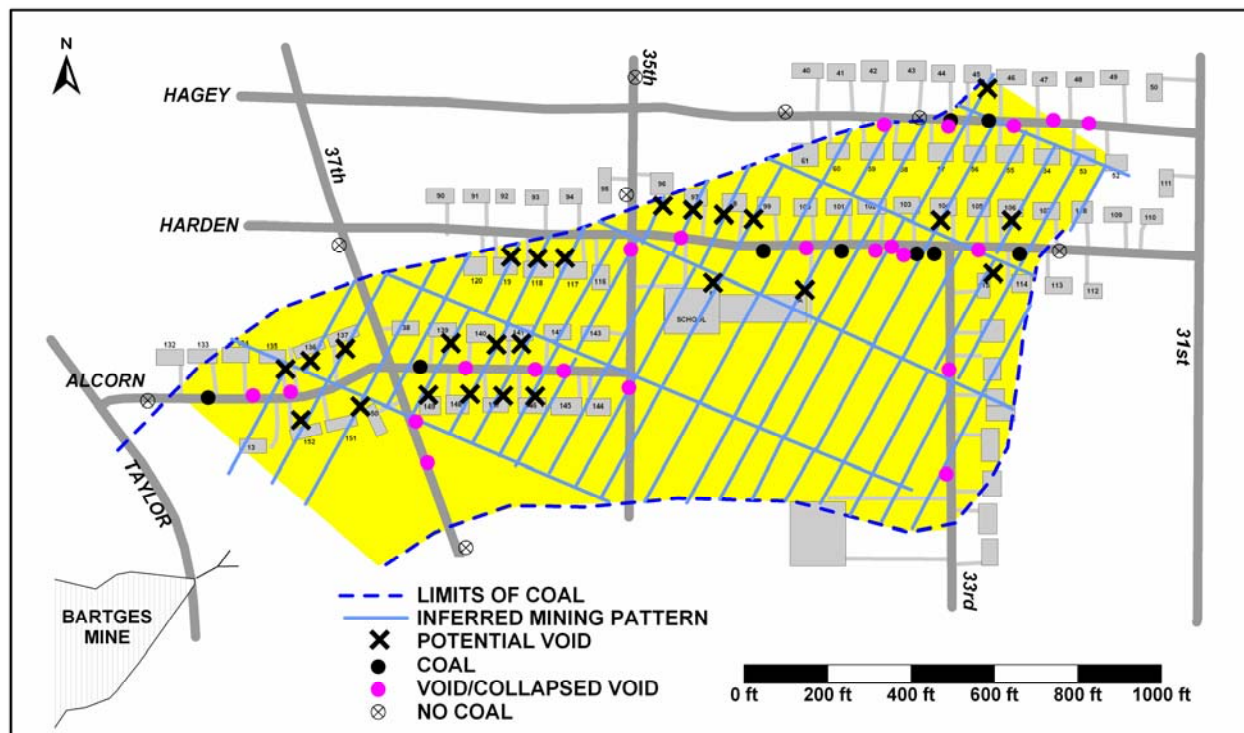


Figure 4. Locations of geophysically derived deep-mine voids.

One important *caveat* must be stressed when reviewing these data; these profile lines were collected in front of existing homes not over the footprint of these homes and these interpretations are based on the projection of the phenomenon to the subsurface of the homes. It is very reasonable to assume that a subsurface phenomenon may project into the front yard of a home and not exist beneath the home. Further, a home may be located on top of a phenomenon that did not project into the front yard and thus was not imaged.

Additional analysis of the study area mine can be derived from a review of the 1876 Bartges Mine map, which delineated a mining pattern to the development of the Bartges Mine (DeLong, 1981). Presumably mining in the study area occurred in a pattern similar to that of the Bartges Mine. This assumption is not too difficult to accept since miners often exploit coal preferential to butt and face cleat orientations, which would be structurally similar for both mine areas (Figure 5). Further, the presence of coal or voids in borings and the location of geophysically imaged voids show a good agreement with the predicted mine pattern (Figure 5).



greater risk from subsidence. While geophysics cannot replace intrusive confirmation of subsurface voids, this technique can aid in directing future investigations.

With the aid of geophysical techniques, a model of the mining pattern of an area where mine maps are unavailable can be inferred. At the Barberton subdivision, the superimposition of the mining pattern of the adjacent Bartges Mine onto the study area, in addition to the use of boring information and a detailed geophysical analysis provided a realistic model of mining in the area.

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